

Generation of genuine χ -type four-particle entangled state of superconducting artificial atoms with broken symmetry *

Chun-Ling Leng · Qi Guo · Xin Ji · Shou Zhang

Abstract: We propose a scheme for generating a genuine χ -type four-particle entangled state of superconducting artificial atoms with broken symmetry by using one-dimensional transmission line resonator as a data bus. The Δ -type three-level artificial atom we use in the scheme is different from natural atom and has cyclic transitions. After suitable interaction time and simple operations, the desired entangled state can be obtained. Since artificial atomic excited states and photonic states are adiabatically eliminated, our scheme is robust against the spontaneous emissions of artificial atoms and the decays of transmission line resonator.

Keywords: χ -type entangled state · superconducting artificial atom · broken symmetry

1. Introduction

Quantum entanglement, a remarkable and attractive feature of quantum mechanics, plays a significant role not only in testing quantum nonlocality, but also in processing a variety of quantum information tasks [1–5]. Therefore, preparation of various quantum entangled states has been being an important subject in quantum information science since a few decades ago [6–15]. Multi-particle entangled states, such as GHZ state [16], W state [17], cluster state [18], etc, are the fundamental resource of quantum information processing. In the research of faithful teleportation of an arbitrary two-qubit state with multipartite entanglement, Yeo and Chua [19] introduced a genuine four-qubit entangled state $|\chi^{00}\rangle_{3214}$,

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namely χ -type entangled state

$$|\chi^{00}\rangle_{3214} = \frac{1}{2\sqrt{2}}(|0000\rangle - |0011\rangle - |0101\rangle + |0110\rangle + |1001\rangle + |1010\rangle + |1100\rangle + |1111\rangle)_{3214} \quad (1)$$

which can't be transformed into other types of multipartite entangled states by stochastic local operations and classical communication. The state $|\chi^{00}\rangle_{3214}$ has many interesting entanglement properties. It has been shown that a new Bell inequality is optimally violated by $|\chi^{00}\rangle_{3214}$ but not by other types of entangled states [20]. Another important property is that it has the maximum entanglement between qubits (3, 2) and (1, 4), and between (3, 1) and (2, 4). Furthermore, χ -type entangled state also has many applications in quantum dense coding [19] or in quantum secure direct communication [21]. Thus, recent researches have focused on looking for some good methods and systems for generating χ -type entangled state. For example, Yuuki *et al.* [22] and Wang *et al.* [23] separately proposed a scheme for generating χ -type four-photon entangled state by using linear optics elements and photon detectors. Wang *et al.* [24] and Shi *et al.* [25] respectively introduced an approach to realize $|\chi^{00}\rangle_{3214}$ -like state and $|\chi^{00}\rangle_{3214}$ state in ion trap system. Zhang *et al.* [26] proposed a scheme to generate $|\chi^{00}\rangle_{3214}$ state of four atomic qubits via two Bell states in cavity quantum electrodynamics system (QED). Afterwards, Guo [27] *et al.* proposed a scheme to generate χ -type entangled state in circuit QED system.

There are many physical carriers of quantum information, such as photons, atoms and ions, and so on. Among those physical carriers, superconducting artificial atoms (AAs) attract lots of attentions because they have potentially excellent scalability due to well-established microfabrication techniques. In recent years, a new system called circuit QED has been put forward, in which superconducting AAs are fabricated inside transmission line resonator (TLR). Circuit QED system is analogous to cavity QED, in which superconducting AAs play the role of atoms in cavity QED system. This architecture is considered as a promising candidates for implementing quantum information processing [28–30] because it strongly inhibits spontaneous emission [31], allows high-fidelity quantum nondemolition measurements of multiple qubit states [32], and can couple qubits separated by centimeter-scale distances [33, 34].

In this paper, we propose a new scheme to create genuine χ -type entangled state of superconducting AAs. It is generally known that artificial solid-state atoms with long-lived internal states are suitable for the storage of quantum information. In addition, our scheme

can obtain both the controllable and selective interqubit coupling, meanwhile the operations are simple, which is helpful to the scalable quantum information processing. We encode the quantum information on the ground states, which can greatly reduce the effect of artificial atomic spontaneous emission on the results, and we can generate the χ -type four-particle entangled state with high fidelity. This paper is arranged as follows. Firstly, the fundamental model and the Hamiltonian of the system are introduced. Then, we show how to prepare the χ -type four-particle entangled state of superconducting AAs with broken symmetry in one-dimensional TLR. Finally, we analyze the performance and the experimental feasibility of the scheme, and give a conclusion.

2. The fundamental model and Hamiltonian

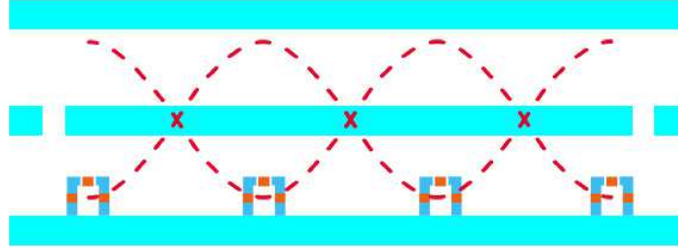


FIG. 1: The schematic setup for generating genuine χ -type four-particle entangled state. Four Δ -type three-level artificial atoms are fabricated inside a one-dimensional transmission line resonator.

The schematic setup for generating genuine χ -type entangled state of AAs is shown in Fig. 1. There are four three-level AAs fabricated inside a one-dimensional TLR. The level configuration of the AA interacting with TLR is shown in Fig. 2. The states $|g_l\rangle$ and $|s_l\rangle$ are two ground levels and $|r_l\rangle$ is an excited level of the AAs. This kind of “artificial atoms” can be made of superconducting three-junction flux qubit circuits [35]. For natural three-level atoms, because of the optical selection rule, the optical transition between the lowest two levels is forbidden. In contrast to the natural atoms, the potential energies for superconducting flux qubit circuits can be artificially controlled. When the reduced bias magnetic flux $f = \Phi/\Phi_0 = 1/2$, where Φ is the static magnetic flux applied to the loop and Φ_0 is the magnetic-flux quantum, artificial atom owns the parity symmetries, and the

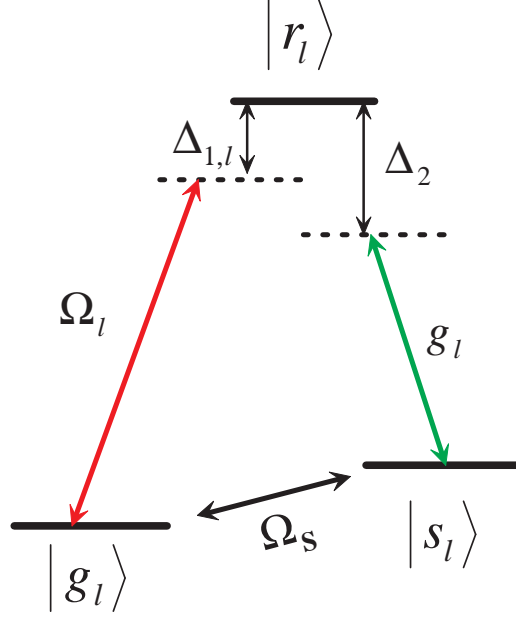


FIG. 2: The level configuration of Δ -type three-level artificial atom.

transitions of lowest three levels behave like a Λ -type or ladder-type natural atom. In this case, the dipole transition $|g_l\rangle \leftrightarrow |s_l\rangle$ is forbidden, while the other two transitions $|g_l\rangle \leftrightarrow |r_l\rangle$ and $|s_l\rangle \leftrightarrow |r_l\rangle$ are allowed. However, when $f \neq 1/2$, the parity symmetry is broken for the interaction Hamiltonian. Therefore, all three dipole transitions among $|g_l\rangle \leftrightarrow |s_l\rangle$, $|s_l\rangle \leftrightarrow |r_l\rangle$ and $|r_l\rangle \leftrightarrow |g_l\rangle$ are possible, allowing the artificial atom to be Δ -type[29].

The transition $|g_l\rangle \leftrightarrow |r_l\rangle$ of qubit l is driven by the classical field with Rabi frequency Ω_l . The transition $|s_l\rangle \leftrightarrow |r_l\rangle$ of qubit l is coupled to TLR with the coupling constant g_l . The frequency detunings between the artificial atomic transitions $|g_l\rangle \leftrightarrow |r_l\rangle$, $|s_l\rangle \leftrightarrow |r_l\rangle$ and the relevant classical field and TLR are denoted as $\Delta_{1,l}$ and Δ_2 , respectively. In the interaction picture, the Hamiltonian describing the AAs-field interaction[36] is

$$H_{\text{int}} = \sum_{l=1}^4 (e^{i\Delta_{1,l}t} \Omega_l |r_l\rangle \langle g_l| + g_l a e^{i\Delta_2 t} |r_l\rangle \langle s_l| + \Omega_s |s_l\rangle \langle g_l| + \text{H.c.}). \quad (2)$$

For the sake of simplicity, we assume $g_1 = g_2 = g_3 = g_4 = g$ in this paper.

Under the conditions $\Delta_{1,l} \gg \Omega_l$, $\Delta_2 \gg g$, the upper level $|r_l\rangle$ in the Hamiltonian H_{int} can

be adiabatically eliminated, leading to the couplings between the two ground states

$$H'_{\text{int}} = - \sum_{l=1}^4 [\eta_l |g_l\rangle\langle g_l| + \xi a^\dagger a |s_l\rangle\langle s_l| + \lambda_l (a^\dagger S_l^+ e^{-i\delta_l t} + \text{H.c.}) - (\Omega_S S_l^+ + \text{H.c.})], \quad (3)$$

where

$$\begin{aligned} \eta_l &= \frac{\Omega_l^2}{\Delta_{1,l}}, \\ \xi &= \frac{g^2}{\Delta_2}, \\ \lambda_l &= \frac{\Omega_l g}{2} (\Delta_{1,l}^{-1} + \Delta_2^{-1}), \\ \delta_l &= \Delta_2 - \Delta_{1,l}, \\ S_l^+ &= |s_l\rangle\langle g_l|, \quad S_l^- = |g_l\rangle\langle s_l|. \end{aligned} \quad (4)$$

Next, we define the new basis

$$|+l\rangle = \frac{1}{\sqrt{2}}(|g_l\rangle + |s_l\rangle), \quad |-l\rangle = \frac{1}{\sqrt{2}}(|g_l\rangle - |s_l\rangle), \quad (5)$$

The Hamiltonian rewritten in new basis is

$$\begin{aligned} H^{\text{new}} &= - \sum_{l=1}^4 \left\{ \frac{\eta_l}{2} (\sigma_l^+ \sigma_l^- + \sigma_l^- \sigma_l^+ + \sigma_l^+ + \sigma_l^-) \right. \\ &\quad + \frac{\xi}{2} a^\dagger a (\sigma_l^+ \sigma_l^- + \sigma_l^- \sigma_l^+ - \sigma_l^+ - \sigma_l^-) \\ &\quad + \lambda_l e^{i\delta_l t} a (\sigma_{z,l} + \frac{1}{2} \sigma_l^- - \frac{1}{2} \sigma_l^+) \\ &\quad + \lambda_l e^{-i\delta_l t} a^\dagger (\sigma_{z,l} + \frac{1}{2} \sigma_l^+ - \frac{1}{2} \sigma_l^-) \\ &\quad \left. - 2\Omega_S \sigma_{z,l} \right\}, \end{aligned} \quad (6)$$

where $\sigma_{z,l} = \frac{1}{2}(|+l\rangle\langle +l| - |-l\rangle\langle -l|)$, $\sigma_l^+ = |+l\rangle\langle -l|$ and $\sigma_l^- = |-l\rangle\langle +l|$.

In the interaction picture with reference to $H_0^{\text{new}} = \sum_{l=1}^4 2\Omega_S \sigma_{z,l}$, the Hamiltonian is reduced to

$$\begin{aligned} H_{\text{int}}^{\text{new}} &= - \sum_{l=1}^4 \left\{ \frac{\eta_l}{2} (e^{i\Omega_S t} \sigma_l^+ \sigma_l^- + e^{-i\Omega_S t} \sigma_l^- \sigma_l^+ \right. \\ &\quad + e^{i2\Omega_S t} \sigma_l^+ + e^{-i2\Omega_S t} \sigma_l^-) \\ &\quad \left. + \frac{\xi}{2} a^\dagger a (e^{i\Omega_S t} \sigma_l^+ \sigma_l^- + e^{-i\Omega_S t} \sigma_l^- \sigma_l^+ \right. \end{aligned}$$

$$\begin{aligned}
& -e^{i2\Omega_S t} \sigma_l^+ - e^{-i2\Omega_S t} \sigma_l^-) \\
& + \lambda_l e^{-i\delta_l t} a^\dagger (\sigma_{z,l} + \frac{1}{2} e^{-i2\Omega_S t} \sigma_l^- - \frac{1}{2} e^{i2\Omega_S t} \sigma_l^+) \\
& + \lambda_l e^{i\delta_l t} a (\sigma_{z,l} + \frac{1}{2} e^{i2\Omega_S t} \sigma_l^+ - \frac{1}{2} e^{-i2\Omega_S t} \sigma_l^-) \}.
\end{aligned} \tag{7}$$

Assume that $2\Omega_S \gg \delta_l, \lambda_l, \eta_l, \xi$, we can neglect the terms oscillating fast. Then $H_{\text{int}}^{\text{new}}$ reduces to

$$H_{\text{int}}^{\text{new}} = - \sum_{l=1}^4 \frac{\lambda_l}{2} (e^{i\delta_l t} a + e^{-i\delta_l t} a^\dagger) (S_l^+ + S_l^-). \tag{8}$$

In the case $\delta_l \gg \lambda_l/2$, there is no energy exchange between the artificial atomic system and the resonator. The effective Hamiltonian is given by

$$\begin{aligned}
H_{\text{eff}}^{\text{new}} &= \sum_{l=1}^4 \frac{(\lambda_l)^2}{4\delta_l} (|s_l\rangle\langle s_l| + |g_l\rangle\langle g_l|) \\
&+ \sum_{\substack{l,m=1(l \neq m)}}^4 \frac{\lambda_l \lambda_m}{4} (\delta_l^{-1} + \delta_m^{-1}) \\
&(e^{-i(\delta_l - \delta_m)t} S_l^+ S_m^+ + e^{-i(\delta_l + \delta_m)t} S_l^+ S_m^- \\
&+ \text{H.c.}).
\end{aligned} \tag{9}$$

3. Generation of the χ -type four-particle entangled state

In this section, we will show how to prepare the χ -type four-particle entangled state. In the strong driving regime, *i.e.* $2\Omega_S \gg \delta_l, \lambda_l, \eta_l, \xi$, the evolution operator of the system is

$$\begin{aligned}
U(t) &= e^{-iH_0^{\text{new}} t} e^{-iH_{\text{eff}}^{\text{new}} t}, \\
H_0^{\text{new}} &= \sum_{l=1}^4 2\Omega_S \sigma_{z,l}, \\
H_{\text{eff}}^{\text{new}} &= \sum_{l=1}^4 \alpha (|s_l\rangle\langle s_l| + |g_l\rangle\langle g_l|) \\
&+ \sum_{\substack{l,m=1(l \neq m)}}^4 \beta (e^{-i(\delta_l - \delta_m)t} S_l^+ S_m^+ \\
&+ e^{-i(\delta_l + \delta_m)t} S_l^+ S_m^- + \text{H.c.}),
\end{aligned} \tag{10}$$

where $\alpha = \frac{(\lambda_l)^2}{4\delta_l}$, $\beta = \frac{\lambda_l \lambda_m}{4} (\delta_l^{-1} + \delta_m^{-1})$.

Through a suitable choice of the Rabi frequencies and detunings of the classical fields, we can use this system to carry out the selective coupling between arbitrarily two qubits.

Firstly, we apply classical pulses to the AAs in TLR simultaneously. Among them, we let $\Omega_1=\Omega_2=\Omega$, $\Omega_3=\Omega_4=\Omega'$, $\Delta_{1,1}=\Delta_{1,2}=\Delta_1$, $\Delta_{1,3}=\Delta_{1,4}=\Delta'_1$ and $|\Delta_1 - \Delta'_1| \gg |\beta_{a,b}|$ ($a=1, 2$ and $b=3, 4$). In this case, AA 1(3) is only coupled to 2(4), while 1 and 2 are decoupled to AAs 3, 4. The evolution operator of the system is

$$\begin{aligned}
U(t) &= e^{-iH_0^{\text{new}}t} e^{-iH_{\text{eff}}^{\text{new}}t}, \\
H_0^{\text{new}} &= \sum_l^4 2\Omega_S \sigma_{z,l}, \\
H_{\text{eff}}^{\text{new}} &= \alpha \sum_{l=1}^2 (|s_l\rangle\langle s_l| + |g_l\rangle\langle g_l|) \\
&\quad + \alpha' \sum_{l=3}^4 (|s_l\rangle\langle s_l| + |g_l\rangle\langle g_l|) \\
&\quad + \beta(S_1^+ S_2^+ + S_1^+ S_2^- + \text{H.c}) \\
&\quad + \beta'(S_3^+ S_4^+ + S_3^+ S_4^- + \text{H.c}), \tag{11}
\end{aligned}$$

where α' and β' have the same formulas as α and β with parameter values Ω' and Δ' instead of Ω and Δ respectively.

Assume that the four AAs are initially in the state $|gggg\rangle_{1234}$. After an interaction time t_1 the state of the system is

$$\begin{aligned}
|gggg\rangle_{1234} &\rightarrow e^{-i2\alpha t_1} e^{-i2\alpha' t_1} \\
&\quad \{ \cos(\beta t_1) [\cos(\Omega_S t_1) |g_1\rangle - i \sin(\Omega_S t_1) |s_1\rangle] \\
&\quad [\cos(\Omega_S t_1) |g_2\rangle - i \sin(\Omega_S t_1) |s_2\rangle] \\
&\quad - i \sin(\beta t_1) [\cos(\Omega_S t_1) |s_1\rangle - i \sin(\Omega_S t_1) |g_1\rangle] \\
&\quad [\cos(\Omega_S t_1) |s_2\rangle - i \sin(\Omega_S t_1) |g_2\rangle] \} \\
&\quad \{ \cos(\beta' t_1) [\cos(\Omega_S t_1) |g_3\rangle - i \sin(\Omega_S t_1) |s_3\rangle] \\
&\quad [\cos(\Omega_S t_1) |g_4\rangle - i \sin(\Omega_S t_1) |s_4\rangle] \\
&\quad - i \sin(\beta' t_1) [\cos(\Omega_S t_1) |s_3\rangle - i \sin(\Omega_S t_1) |g_3\rangle] \\
&\quad [\cos(\Omega_S t_1) |s_4\rangle - i \sin(\Omega_S t_1) |g_4\rangle] \}. \tag{12}
\end{aligned}$$

The common phase factor $e^{-i2\alpha t_1} e^{-i2\alpha' t_1}$ can be discarded. When the interaction time t_1 satisfies $\Omega_S t_1 = n\pi$ (n is an integer) and $\beta t_1 = \beta' t_1 = \pi/4$, the four-atom state becomes

$$|gggg\rangle_{1234} \rightarrow \frac{1}{2} (|gggg\rangle - i|ggss\rangle - i|ssgg\rangle - |ssss\rangle)_{1234}. \tag{13}$$

Then, we let $\Omega_2=\Omega_3=\Omega$, $\Omega_1=\Omega_4=0$, and $\Delta_{1,2}=\Delta_{1,3}=\Delta_1$. And we only apply two strong classical pulses to the AA 2 and AA 3 simultaneously. In this step, only the interaction

between AA 2 and AA 3 can happen. After the operation time t_2 under the condition $\Omega_S t_2 = n\pi$, $\beta t_2 = \pi/4$, we obtain an entangled state

$$|\chi^{00}\rangle'_{1234} = \frac{1}{2\sqrt{2}}(|gggg\rangle - i|gssg\rangle - i|gsgs\rangle - |sgsg\rangle - i|ssgg\rangle - |sgsg\rangle - |ssss\rangle + i|sggs\rangle)_{1234}. \quad (14)$$

Through a local unitary transformation on AAs 1 and 3 $\{|g\rangle \rightarrow |g\rangle, |s\rangle \rightarrow i|s\rangle\}$, we can obtain the genuine four-qubit χ -type entanglement state

$$|\chi^{00}\rangle_{3214} = \frac{1}{2\sqrt{2}}(|gggg\rangle - |ggss\rangle - |sgsg\rangle + |sggs\rangle + |ssgg\rangle + |gssg\rangle + |ssss\rangle + |sgsg\rangle)_{3214}. \quad (15)$$

4. Discussion and conclusion

In the above part, we have assumed the interacting times can be controlled accurately. But in the realistic experiment, the interacting time of each step can't be controlled perfectly, and the time errors will inevitably exist. For the sake of convenience, we define the time error rate as $n_i = \Delta t_i / t_i$ ($i = 1, 2$), Δt_i is the time error in the i th step. Considering time errors, we rethink the process of derivation and get a real state $|\chi\rangle_{\text{real}}$. The fidelity is defined as

$$F = |_{3214}\langle\chi^{00}|\chi\rangle_{\text{real}}|^2. \quad (16)$$

For an intuitive grasp of the effect of the time errors on the fidelity, the total fidelity as function of n_i is given in Fig. 3. It can be seen from Fig. 3 that the fidelity decreases slightly with the increase of the interaction time errors. Under the condition $n_1=0.02, n_2=0.02$, the fidelity can still reach 0.96.

Now we briefly discuss the feasibility of the present scheme based on the current available parameters. At the first step, we set $\Omega_1=\Omega_2=\Omega=g$, $\Omega_3=\Omega_4=\Omega'=0.725g$, $\Delta_{1,1}=\Delta_{1,2}=10g$, $\Delta_{1,3}=\Delta_{1,4}=10.5g$, and $\Delta_2=11g$. Then we have $\beta \simeq \beta' \simeq 4.56 \times 10^{-3}g$, so the time of the first step is $t_1=\pi/4\beta \simeq 0.172 \times 10^3/g$. At the second step, we set $\Omega_2=\Omega_3=\Omega=g$, $\Omega_1=\Omega_4=0$, $\Delta_{1,2}=\Delta_{1,3}=\Delta=10g$ and $\Delta_2=11g$. Then we have $\beta \simeq 4.56 \times 10^{-3}g$, so the time of the second step is $t_2=\pi/4\beta \simeq 0.172 \times 10^3/g$. It is known that, with current experimental techniques, the coupling constant between the flux qubit and the data bus can reach $g=2\pi \times 200\text{MHz}$ [37]. Therefore, in the first step, the operation time is about $t_1=0.137\mu s$. And in the second step,

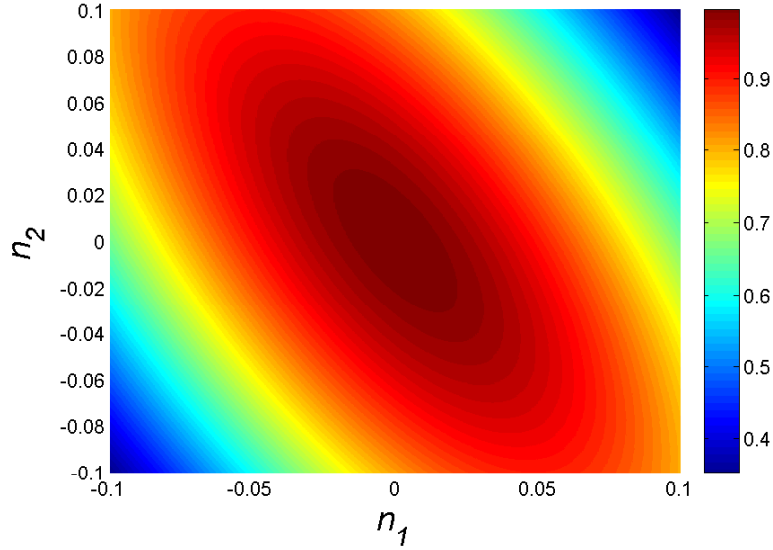


FIG. 3: Density plot of the fidelity as a function of time error rates n_1 and n_2 .

the parameters remain unchanged, then the operation time t_2 is the same as t_1 . The total operation time is $T=t_1 + t_2=0.274\mu s$. However, in the experiment the relaxation time τ_r and dephasing time τ_d of the flux qubit can reach $\tau_r \sim \tau_d=1.5\mu s$ [38]. Thus, it is obvious that $T = t_1 + t_2 \ll \tau_r$.

In conclusion, we have proposed a new scheme to create a genuine χ -type four-particle entangled state of superconducting AAs in TLR with broken symmetry, in which selection rules can not hold and cyclic transition structures are generated. The distinguished feature of the present scheme is that artificial atomic excited states and photonic states are adiabatically eliminated, so our scheme is robust against the spontaneous emissions of AAs and the decays of TLR. We have analyzed the performance and the experimental feasibility of the scheme, and shows that our scheme is feasible under existing experimental conditions.

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